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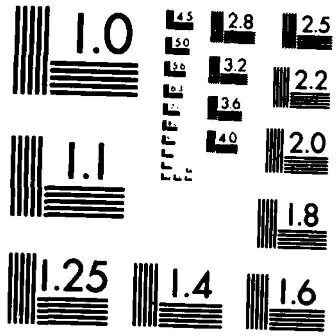

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AN EVALUATION OF ALTERNATIVE METHODOLOGIES FOR COMPUTING F100 ENGINE REQUIREMENTS

THESIS

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AN EVALUATION OF ALTERNATIVE METHODOLOGIES FOR COMPUTING F100 ENGINE REQUIREMENTS

THESIS

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

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Patrick G. Collins, B.S.

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Abstract

The purpose of this research was to compare different methodologies for computing operational spares requirements for the F100-PW-100 jet engine, and to recommend a specific inventory model to be used by the Air Force to compute requirements for all modular engines.

The models to be compared were the Engine Availability Concept, currently being used to compute F100 requirements, and Dyna-METRIC, which shows promise for use in requirements computations, but is now used only for capability assessment. The research found that the Engine Availability Concept has apparently serious flaws that precluded comparison of the models using the scenario developed for the experiment. The study recommends that use of, and reliance on, the Engine Availability Concept be suspended pending completion of further research.

The Engine Availability Concept model is time and labor intensive, and requires considerable user experience to operate. The model relies on an apparently unsupported assumption that engine module stock levels computed for one phase of a given wartime scenario can be used without modification in another phase. In addition, the model

contains no provision for computing module requirements in situations involving more than two echelons of maintenance and supply.

AN EVALUATION OF ALTERNATIVE METHODOLOGIES
FOR COMPUTING F100 ENGINE REQUIREMENTS

I. Introduction

General Issue

The Air Force is constantly striving to keep its logistics system responsive to changes in technology and requirements. The objective is to support operational forces economically to maintain both readiness during peacetime and combat effectiveness in war. This has resulted in a policy of selective management of certain high value weapon system components, including aircraft propulsion systems (6:5).

The high cost of engines makes selective management necessary. For example, the F100-PW-100 augmented turbofan engine used in the F-15 fighter costs $2,650,258 (1:50). Large inventories of these engines are prohibitively expensive. Procurement and inventories must be kept at the lowest levels possible while minimizing the risk of shortages in the event of war. The goals of peacetime efficiency and wartime effectiveness make it critical that the best methodology for requirements computations is employed.

Prior to 1984, the Air Force computed all engine requirements based on the greater of the estimates of demand

for peacetime or war (7:2). This concept did not take into consideration the dynamic environment of the transition between peacetime and war. The Alternate Engine [illegible], called the Engine Availability Concept (EAC), was developed to more realistically model the dynamics of war [illegible] quarters United States Air Force approved EAC for use [illegible] 1984 and Air Force Logistics Command (AFLC) [illegible] acquisition phase of the F100 and F1[illegible] engine [illegible]. AFLC is now in the process of developing the [illegible] in the distribution of the F100 engine. The [illegible] tion of the EAC is that the Air Force must have [illegible] engines on hand to support the most demanding [illegible] peacetime, surge (the first 30 days of war), or sustainment (wartime after the first 30 days). It uses a steady state, stochastic inventory model called Modified Multi-Echelon Technique for Recoverable Item Control (Mod-METRIC) in which component failure rates are driven by a time invariant proba-bility distribution. Mod-METRIC is used for the peace and sustainment phases, and a deterministic Demand/Resupply model is used for the surge phase (3). The EAC appears to be an effective and useful model, but user time is excessive and aggregation of the requirements from all the bases is labor intensive. Air Force Logistics Command is seeking to reduce the time and labor needed to compute engine requirements.

The development of non-stationary models such as Dyna-METRIC holds promise for the simplification of the requirements determination process (11; 2).

Dyna-METRIC and Mod-METRIC are similar in their theoretical bases. Both models use the relationship between line replaceable units (LRUs) and shop replaceable units (SRUs) to compute the average repair/resupply quantity for individual items. Mod-METRIC's objective function is to minimize base level back orders of LRUs subject to a budget constraint. Dyna-METRIC also computes base level LRU supply statistics and estimates operational capability. Both models consider multiple echelons, i.e. levels of supply and repair. Mod-METRIC provides a two echelon system consisting of bases and a depot. Dyna-METRIC provides the option of a two level system similar to the Mod-METRIC model, or a three level system consisting of bases, Centralized Intermediate Repair Facilities (CIRFs), and depots. The Dyna-METRIC environment is fluid and includes time-dependent flying programs, repair and transportation times, deployments, and pipeline interruptions. Dyna-METRIC can be operated in either of two modes. The assessment mode estimates the operational capability provided by given stock levels of components. The requirements mode computes stock levels needed to support a stated level of operations (17:vi).

Both Mod-METRIC and Dyna-METRIC assume the breakage of parts is the only thing that prevents an aircraft from flying. Each model also has individual specific operational assumptions which, as with any model, inhibit their ability to represent real world situations. Both models have been in use for some time and their utility is well known. However, the management of modular engines such as the F100 is different than management of most other items. These engines require computation of engine and module requirements at the same time (6:28). For management purposes, these engines are considered to be both components of aircraft and end items. Because of this duality, a mathematical model for computing engine requirements must be thoroughly validated and tested before being adopted as a matter of policy and put into general use.

Specific Problem

Within the general issue of ensuring efficiency and effectiveness is the problem of evaluating the available inventory models and selecting the one that best meets the needs of the Air Force.

Research Objectives

The objective of this research is to recommend to the Air Staff, and Headquarters AFLC, a specific model for calculating inventory requirements for spare F100 aircraft engines and modules.

Research Questions

To met the stated research objective, the following research questions must be answered:

1. What methodology should be used to compute aircraft engine requirements, that is, which model should the Air Force adopt?

2. Given the selection of a model, what specific model parameters should be used to compute requirements for spare engines and modules?

Investigative Questions

To compare the computational methodologies of the models and determine the relative value of their final products, the following investigative questions will have to be answered.

1. Will Dyna-METRIC and EAC computations result in the same requirements, given equal parameters?

2. Can Dyna-METRIC parameters be adjusted to give the same level of support as EAC, but at less cost?

Scope and Limitations

This research is limited to consideration of the Dyna-METRIC (Version 4) and EAC models. Background on these models is included in Chapter II. Other models may exist which are superior to either of those considered, but the effort necessary to identify and test those models is beyond the scope of this research. In addition, this research is

limited to modeling the distribution of F100 jet engines and modules. Specific limitations of scenarios and parameters are discussed in Chapter III.

II. Background

Overview

A general understanding of the origins and theoretical bases of Dyna-METRIC and the Engine Availability Concept is necessary to perform an evaluation of the models. To aid in the development of that understanding, a brief history of the models is presented, including the (s-1,s) Inventory Policy, Base Stockage Model, and METRIC. The mathematical extensions of METRIC, Mod-METRIC and Dyna-METRIC, are then discussed in detail, including a description of the models, their assumptions, and limitations.

History of the Models

The history of Mod-METRIC, Dyna-METRIC, and the other members of the METRIC family of models goes back to a theorem published by C. Palm in 1943. In its original form, Palm's Theorem dealt with steady-state Poisson processes and was used to describe the number of telephone exchanges in use, providing a mathematical way of determining how many exchanges are required to handle an anticipated demand.

Palm's Theorem found wide-spread application, due largely to its use of a Poisson distribution to model arrival processes (5:1). The Poisson distribution is a good approximation of an arrival process in which a number of independent entities each have a small probability of

generating an event in a specified time interval (5:10). Although Palm's Theorem described the number of telephone trunk lines in use, it can be generalized for use in the inventory system for expensive reparable items (also called recoverable items) such as aircraft engines and modules.

Palm's Theorem states that:

> . . . if demand is Poisson then the number of units in resupply in the steady state, x, is also Poisson for any distribution of resupply. The Poisson state probability depends on the mean of the resupply distribution, but not on the distribution itself [10:2].

The models ancestral to the METRIC family of models all use generalizations of Palm's Theorem to compute the number of items in the repair cycle of the inventory system. When it is so used, the term "arrival" means that an item has failed and thus generated an arrival at the repair cycle and the term "survival time" is the repair or order time for that arrival, (s-1,s) Inventory Policy and Base Stockage Model. The inventory system for expensive reparables such as aircraft engines and modules is many times modeled with an (s-1,s) inventory policy (5:4). All inventory policies are concerned with the decisions of when and how much to reorder. Interaction between these two decisions adds complexity to attempts at inventory analysis. A special case of this analysis is those items for which the demand is so low and the cost so high that the optimal policy is to place a reorder immediately whenever a demand occurs (10:1).

Under this policy, inventory performance is determined by just one decision, the spare stock, s, provided as protection against stockouts. Since resupply is not instantaneous, s is normally positive. This is a continuous review (s-1,s) inventory policy. Whenever a demand for any number of units is generated, a like number of units is reordered. This restores the stock on hand plus on order, minus backorders, to the spare stock level, s (10:1).

Fenney and Sherbrooke described the supply process for recoverable items as follows:

> When an item fails in the course of base operations, it is examined to determine whether repair is possible at base level. If so, the item is scheduled into base repair and, after a variable lag representing base repair-cycle length, it is returned to a serviceable condition. If base repair is not indicated, the item is either condemned or adjudged NRTS (Not Reparable This Station) and forwarded to the depot for repair action. In the latter cases the base submits a requisition to the depot for a serviceable replacement that will arrive at the base after a variable lag representing base resupply-cycle time (order and shipping time) [9:2].

The objective of Feeney and Sherbrooke's work on the (s-1,s) model was to compute the steady state probability distribution measured at a random point of time for the number of units in resupply, x. This is the only random variable in the model. When s-x is positive it represents stock on hand; when it is negative it represents backorders. The steady state probability distributions for both stock

on hand and backorders are obtained from the steady state distribution for the number of units in resupply (10:2).

In the course of the development of their model, Feeney and Sherbrooke restated Palm's Theorem in terms of inventory control theory. Let s be the spare stock for an item where demands are Poisson with rate λ and the resupply time is an arbitrary probability distribution $\lambda(t)$ with mean T. The steady state probabilities of x units in resupply are given by the Poisson with rate λT, i.e.,

h(x) = steady state probability that x units are in resupply

$$= \frac{\lambda T^{x} e^{-\lambda T}}{x!} \qquad 0 \leq x < \infty \qquad (1)$$

[10:3]

The simple Poisson distribution used in the above theorem can be described as a single customer arriving in each exponentially distributed time interval and placing a single demand.

Feeney and Sherbrooke also generalized Palm's Theorem to any compound Poisson distribution. They visualized the compound Poisson in an inventory problem as a series of customers who demand an amount that has a discrete distribution with any number of parameters (10:5).

The primary difference between the simple and compound Poisson distributions is in the ratio of the variance to the

mean. In a simple Poisson, the variance-to-mean ratio is one. A compound Poisson has a variance-to-mean ratio greater than one. Feeney and Sherbrooke chose the compound Poisson for two reasons:

1. The higher variance-to-mean ratio of the compound Poisson reflected the demand data used in their research.

2. The model concept of a single customer able to order several units at the same time appears to be a reasonable description of many supply processes (10:5-6).

To compute the probability of observing x demands during a given time period when demand has a compound Poisson distribution, let the Poisson customer arrival rate during the time period be λ. There will be x demands if there are x customers and if the y customers order a total of x demands. The probability that y customers order a total of x demands is denoted by the y fold convolution of x, $f^{y*}(x)$. (The y fold convolution of f(x) is the probability distribution of the sum of y samples from f(x)) (9:5). Since the probability that there are y customers and that the y customers order a total of x demands is

$$\frac{\lambda^{y}e^{-\lambda}}{y!} f^{y*}(x) \qquad 0 \leq x \leq \infty \tag{2}$$

the compound Poisson probability of x demands is

$$p(x|\lambda) = \sum_{y-o}^{x} \frac{\lambda^{y}e^{-\lambda}}{y!} f^{y*}(x) \qquad 0 \leq x < \infty \tag{3}$$

The generalization of Palm's Theorem to include compound Poisson distributions can be stated as:

Let s be the the spare stock for an item where demands are compound Poisson with customer arrival rate λ and the resupply time is an arbitrary distribution $\psi(t)$ with mean T. Assume that when a customer is accepted, a resupply time is drawn from $\psi(t)$ that is applicable to all demands placed by that customer. The steady state probabilities of x units in resupply are given by the compound Poisson with rate λT, that is,

$$h(x) = p(x|\lambda T) \qquad 0 \leq x < \infty \tag{4}$$

[10:7]

The Base Stockage Model was developed as a method for determining optimal stock levels, subject to a stated system objective, under the (s-1,s) inventory policy (9:4, 10).

The model performs a marginal analysis for all the items at a given stockage location (e.g. a base) and determines the mix of stock that will result in the lowest level of backorders for a given amount of money (9:14-15).

METRIC

METRIC extends the mathematical approach of the Base Stockage model to include the base-depot supply system. It is capable of determining base and depot stock levels for a group of recoverable items. The model is designed to be

used at the weapon system level, where an item may be demanded at several bases that are supported by a depot. Its purposes are:

1. To determine optimal base and depot stock levels for each item, subject to monetary or performance constraints.

2. Allocate stock between the bases and depot.

3. Assess the system performance and cost of any allocation of stock between bases and depot (18:2).

The objective function is to minimize the expected number of backorders. For a fixed period of time, the number of days on which any unit of any item at any base is backordered are totaled. This number is divided by the length of the period. The expected value of the statistic yields a number that is independent of the period length. It is this value that the model seeks to minimize.

Under this definition, a backorder exists at a point in time if, and only if, there is an unsatisfied demand at base level (18:6).

METRIC Assumptions. The METRIC model contains a number of assumptions (18:6-12; 15:474). These assumptions are:

1. The demand for each item is described by a stationary compound Poisson process. In this case it is a logarithmic Poisson, which can be described as a process in which a batch of demands arrives according to a Poisson

distribution and the number of demands per batch has a logarithmic distribution.

2. Repair times are statistically independent.

3. A failure of one type of item is statistically independent of those that occur for any other type of item.

4. The decision of where repair is to be accomplished (base or depot) depends only on the complexity of the repair.

5. Lateral resupply, i.e., items shipped from one base to another, is ignored.

6. There are no condemnations.

7. The depot does not batch units of a recoverable item for repair unless there is an ample supply of serviceable assets (infinite channel queuing assumption).

8. All items have equal essentiality. (Essentiality ". . . is the relative cost of a backorder on item i at base j compared to a backorder on some standard item" (18:4).

The assumption of a logarithmic Poisson process for item demand allows the flexibility of incorporating more parameters than in the simple Poisson. The state probabilities, i.e., the probability of n demands in a time interval of specified length t, for the logarithmic Poisson process are negative binomial, which are easily computed. In addition, the state probabilities for the two distributions are almost identical for variance-to-mean ratios less than three (the range of interest in this model). To illustrate, the

probability of x demands in the specified time period is given by the negative binomial distribution

$$p(x|\lambda) = [(k+x-1)!/(k-1)!x!][(q-1)^x/q^{k+x}] \quad (5)$$

$$x = 0,1,2,3...,\quad q>1,\quad k>0$$

where $\lambda = k(\ln q)$. The mean is defined as $\emptyset$, which is equal to $k(q - 1)$, where q is the variance-to-mean ratio. This ratio remains constant for any particular item (18:8-9).

METRIC Limitations. At the time METRIC was developed, the assumption of stationary demand over the prediction period was seen as a restriction, but one that could be overcome by using the compound Poisson model in conjunction with a Bayesian probability distribution for true mean demand, thus enabling the representation of more complex demand patterns over an arbitrary-length prediction period (18:9]. The restrictiveness of this assumption when trying to model non-stationary processes eventually led to the development of non-stationary demand models, which are discussed later in this thesis.

The assumption of equal essentiality of items is not appropriate for modular items such as the F100 engine. The advent of modularly designed items led to the development of the next step in the METRIC series, Mod-METRIC.

Mod-METRIC

Muckstadt developed an extension of METRIC that permits consideration of a hierarchical parts structure, i.e., a

multi-indenture system. The objectives of the Mod-METRIC model are to describe the logistics relationship between components and the final assembly, and to compute base and depot stock levels for spares considering that relationship (15:472).

The system structure being modeled by Mod-METRIC is exemplified by modular engines. These engines basically consist of a casing, some external parts, and several modules. When an engine fails, it is removed and replaced with a serviceable engine. This is accomplished on the flightline, hence, the engine is a line replaceable unit (LRU). The unserviceable engine is then examined to determine which module or modules caused the failure. The defective module is removed and replaced with a serviceable module from stock. The defective module is then repaired on base or sent to the depot for repair. Since removal of modules from the engine is accomplished in a shop, (as opposed to on the flightline), the modules are called shop replaceable units (SRUs) (15:473).

Mod-METRIC Assumptions. Mod-METRIC retains most of the METRIC assumptions. The exceptions are that all items are not equally essential and the demand process is Poisson whose mean is a random variable distributed according to a gamma distribution. METRIC used a logarithmic distribution to compound the Poisson demand process. As in METRIC,

demand is assumed to be stationary throughout the prediction period (15:475).

The unequal essentiality of items comes from the relationship between the LRUs and SRUs. In METRIC, a backorder on a module is treated the same as a backorder on an engine. In fact, the lack of an engine grounds an aircraft whereas the lack of a module only delays repair of an engine. The impact of a backorder on engines and modules is not the same. Muckstadt found that to compute the effectiveness of the supply system to meet demands for engines, one must describe the relationship between engines and modules. The equation representing the average resupply time (T_i) expresses this relationship and is the fundamental difference between Mod-METRIC and METRIC. In METRIC the average resupply time is expressed as:

$$T_i = r_i B_i + (1 - r_i)(A_i + \delta(S_o)D) \tag{6}$$

In Mod-METRIC the average resupply time is expressed as:

$$T_i = r_i(R_i + \Delta_i) + (1 - r_i)(A_i + \delta(S_o)D) \tag{7}$$

where r_i = the probability that a failure isolated to a module will be repaired at base level,

R_i = average base repair time if modules are available,

$_i$ = average delay in base engine repair due to unavailability of a needed module,

B_i = average base repair time,

A_i = average order and ship time, and

$\delta(S_o)D$ = expected backorders/expected daily demand at the depot.

Mod-METRIC employs this relationship to determine engine and module stock levels (15:475-477).

The problem of minimizing LRU backorders and setting the optimum stock levels for spare LRUs and SRUs can be stated mathematically as:

$$\min \sum_{i=1}^{M} \sum_{x_i = S_i = 1}^{\infty} (x_i - s_i) p(x_i | \lambda_i T_i)$$

subject to

$$\sum_{i=1}^{M} [c_E s_i + \sum_{j=1}^{N} c_j s_{ij}] = \sum_{j=1}^{N} c_j so_j + c_E s_o \leq c \qquad (8)$$

where

s_i = stock level of spare engines at base i,

c_E = unit cost of end item (engine),

c_j = unit cost of module j, and

C = dollar budget limit [15:477]

<u>Mod-METRIC Limitations</u>. The main limitation of Mod-METRIC is that it assumes a stationary environment, and the Air Force environment is not stationary over time. Stationary models such as Mod-METRIC are useful in times of relatively stable flying activity such as peacetime, or even

wartime after the initial surge period, but at certain points in time, e.g., during the surge period of a war, stationary models either overstate or understate the capability to support a projected level of flying hours (16:1). In short, Mod-METRIC is effective in modeling peacetime or wartime sustained requirements, but is ineffective in modeling the transitional surge period.

Prior to 1984, Air Force policy, as delineated in AFM 400-1, was to set engine requirements to meet the greater of the demand during peacetime or war. This policy did not take into account the changing environment of the surge period. To more realistically model the dynamics of this situation the Air Force adopted the Engine Availability Concept (EAC) in 1984 (2).

Engine Availability Concept

The EAC uses Mod-METRIC to model the relatively stationary periods before and after surge. For the surge period a deterministic model was developed to estimate the number of spares needed at each base during a period of changing levels of flying hours and possible cut-offs of maintenance capability (14).

This model, known as the Demand/Resupply Model, calculates how many spares are needed day by day at each location during the surge period. It compares these demands to the resupply available from all sources and computes the delta, the difference between demand and resupply. The largest

delta is then added to the peacetime requirement as calculated by Mod-METRIC and compared to the sustain requirement calculated by Mod-METRIC. The larger of the two figures then becomes the spares requirement for the item (14).

The model as described deals only with the engines and does not include modules. For any base modeled that has organizational maintenance capability, Demand/Resupply computes the number of spare augmentors (one of the 6 modules in the F100 engine) based on the projected base repair rate. Demand/Resupply does not compute surge requirements for the other modules. Instead, the requirement for these modules is assumed to be the same as the sustain period (as calculated by Mod-METRIC) (14).

Dyna-METRIC

Muckstadt studied the comparative adequacy of steady state (i.e., stationary) versus dynamic models for the stockage requirements application. He demonstrated that steady state models tend to give results that would provide less than adequate supply support during the early portion of the surge period, and much better than planned at the end of the period (16:5-7). This shortcoming heralded the development of non-steady state models, such as Dyna-METRIC.

In general, Dyna-METRIC ". . . was developed to study and predict the readiness of groups of aircraft squadrons as determined by a major subset of logistics resources, namely, those associated with component repair and resupply" (12:2).

Specifically, it is designed to provide a number of new kinds of information to logistics decision makers, quoted here from Pyles:

1. Operational performance measures.
2. Effects of wartime dynamics.
3. Effects of repair capacity and priority repair.
4. Problem detection and diagnosis.
5. Assessments or requirements [16:3].

Dyna-METRIC's four key capabilities, again quoting Pyles, are:

1. Forecasting component pipelines.
2. Estimating aircraft availability and sorties.
3. Identifying problem parts.
4. Suggesting cost-effective stock purchases [16:8].

Dyna-METRIC portrays component support processes as a flow of components through a network of pipelines. Components flow through the network as they are repaired or replaced. Each segment of the pipeline is characterized by either a random or deterministic delay time. Some delay times vary by component; others vary depending on the base being assessed. Failed components enter the pipeline network at the bases' flightlines where they are removed from aircraft and replaced with serviceable components drawn from base supply.

The bases may have shops to repair failed components. Deployed units' repair capability may be delayed while the repair capability is deployed and made operational.

Components removed from aircraft are repaired locally or sent to other repair facilities. Locally repaired components are returned to base stock. Components that cannot be repaired locally are declared NRTS (not reparable this station) and sent either to a centralized intermediate repair facility (CIRF), or a depot. When a component is determined to be NRTS, a replacement is immediately requested from the facility that will receive it. That facility immediately ships the base a serviceable spare, if one is available. If none is available, the CIRF ships one to the base as soon as possible. Once the failed component reaches the CIRF, it is repaired and returned to CIRF stock, or condemned if beyond repair.

If the repair cannot be performed at the CIRF, the component is sent to the depot, either directly from the base, or from the CIRF. Shipments direct to the depot from bases arise from those situations in which the CIRF does not have the required repair capability. CIRF to depot shipments result when the CIRF fails in its repair attempt. A demand is then placed on the depot for a replacement item, which is shipped to the requisitioning facility. The failed component is repaired at the depot and returned to depot stock [16:9-11].

Hillestad and Carrillo give the theoretical development of the dynamic queuing equations central to the workings of Dyna-METRIC. They demonstrated how Palm's Theorem could be

extended to the dynamic wartime situation [16:12]. Crawford includes an extensive discussion of the dynamic form of Palm's Theorem.

In the Dyna-METRIC model, the daily demand rate, d(t), is a function of time so that

d(t) = (failures per flying hour)
  x (flying hours/sortie at time t)
  x (number of sorties per aircraft per day
   per day at time t)
  x (number of aircraft at time t)
  x (quantity of the component on the aircraft)
  x (percentage of aircraft with the component) (9)

The steady state models used a constant repair time, T. Dyna-METRIC uses the probability that a component entering repair at time s is still in repair at time t. This probability function, $\bar{F}(t,s)$, is called the repair function and is defined as:

$\bar{F}(t,s)$ = p(component entering at s is still in repair at t)

= p(repair time > t-s when started at s)

The repair function can be changed to represent various time dependencies in component repair, but it is always assumed to be independent of the failure process (demand function) (12:8-11).

Dyna-METRIC combines the repair and demand functions to determine the average number of parts in the pipeline. Considering only those components that arrived in time

interval s, the expected number of components in the pipeline at time t is given by:

$$\Delta\lambda(t,s) = d(s) \times F(t,s) \times \; s, \qquad (10)$$

where $\Delta\lambda(t,s)$ = expected number of components in the repair pipeline at time t that arrived during the interval around s,

$d(s)$ = daily failure rate at time s,

$\overline{F}(t,s)$ = probability of component not out of repair by time t, and

Δs = interval of time centered at s.

Dyna-METRIC assumes that the number of failures arriving in the interval s is independent of the number of failures arriving in similar intervals centered at times other than s. This independent increment assumption is inherent to the Poisson process. This assumption results in an overstatement of requirements in situations such as those in which aircraft attrition due to component failures reduces the number of sorties flown. In this instance the degraded sortie rate (which drives component failures) is a function of previous component removals resulting in an overstatement of the number of components in the pipeline. Hillestad determined that this is not a serious problem for most Dyna-METRIC users. When serious shortages of supply resources are modeled, a second iteration is needed to achieve a more accurate answer [12:11].

Given that the assumption is reasonable, the sum of the contributions of all the intervals leads to the average number of components in the repair pipeline at time t, $\lambda(t)$, which is:

$$(t) = \int_{0}^{t} d(s)\overline{F}(t,s)ds \tag{11}$$

With an assumption that the component failure probability distribution is Poisson, $\lambda(t)$ is the mean of a time-varying Poisson process. That is to say, the probability of k components in repair at time t is

$$P(k) = [\lambda(t)^{k}e^{-\lambda(t)}]/k! \tag{12}$$

where

$$(t) = \int_{0}^{t} d(s)\overline{F}(s,t)ds \tag{13}$$

[12:11-12]

Compound Poisson distributions satisfy the independent increment assumption and result in pipeline distributions such as the negative binomial, which is given by

$$P(k) = [(r+k-1)!/(r-1)!k!][p^{k}/q^{r+k}] \tag{14}$$

where

q = variance to mean ratio ($q > 1$)

$$r = \lambda(t)/q-1 \tag{15}$$

$$p = q-1 \tag{16}$$

[13:9-13]

Combining the pipeline quantities with the supply levels at the same instant of time permits calculation of certain measures of availability or shortage of individual components. The component performance measures are calculated for a given supply level, S(t). This level is established to protect against shortages due to components being in repair or on order. When the number of components in repair and on order at time t exceeds S(t), the system enters into a backorder state. If components are backordered some aircraft will be missing possibly mission-critical parts, thus reducing the number of fully mission capable (FMC) aircraft. This results in fewer sorties (if the aircraft cannot fly), or in aircraft that cannot fully meet mission needs--they are not fully mission capable (NFMC) (16:12).

Component Performance Measures. Dyna-METRIC computes the following component performance measures:

DT(t) = Average cumulative demands by time t. It is derived from the daily demand rate, d(s).

$$DT(t) = \int_{0}^{t} d(s)ds \tag{17}$$

The remaining performance measures use the average pipeline quantity, the stock level, and the probability distribution $P(k/\lambda(t))$ chosen from the Poisson distribution as in Equation 12, or the negative binomial distribution as in Equation 14 (14:24-25).

R(t) = Ready rate at time t, or the probability that an item observed at time t has no backorders.

$$R(t) = \sum_{k=o}^{s(t)} (P(k/\lambda(t))) \tag{18}$$

FR(t) = Fill rate at time t, or the probability that a demand at time t can be filed immediately from stock on hand.

$$FR(t) = \sum_{k=o}^{s(t)} (P(k/\lambda(t))) \tag{19}$$

EB(t) = Expected backorders, or the average number of shortages of a component at time t.

$$EB(t) = (t) - S(t) + \sum_{k=o}^{s(t)-1} (S(t) - k)\ P(k/\lambda(t)) \tag{20}$$

VB(t) = Variance of the backorders, a measure of the random variation of backorders.

$$VB(t) = \sum_{k=S(t)-1}^{\infty} [k-s(t)]^2\ P(k/\lambda(t)) - [EB(t)]^2 \tag{21}$$

The performance measures described above can be computed for each component for each location at any point in time (12:24-28).

System Performance Measures. The model adds all the pipeline segments to estimate the total pipeline as applies to each base and computes the probability that a given number of components are in repair and on order at each base (16:12).

The model next forecasts how the components in the pipeline generate backorders, using the total pipeline probability distributions and the available stock at each location. The "holes" in aircraft caused by these backorders are then distributed across aircraft under alternative policies of either no cannibalization or full cannibalization of components. For the no cannibalization alternative it is assumed that failed components occur randomly across aircraft at each base. Under the full cannibalization policy the model assumes that the "holes" are consolidated onto the fewest aircraft possible in order to keep more aircraft fully mission capable. The model then forecasts, assuming full cannibalization, the number of fully mission capable sorties that can be flown (16:12-14).

The following set of system performance measure equations were developed by Hillestad and Carrillo and repeated by Hillestad:

1. The average number of systems not mission capable (NMC) with no cannibalization, EN(t).

EN(t) gives the average combined effect of recoverable item shortages on the aircraft those items support. Given that NA(t) is the number of aircraft at time t, and that there are N types of recoverable items required on each aircraft, assume that the shortages of any one of these items will make the aircraft NMC. With no cannibalization, these shortages cannot be consolidated among the aircraft.

The probability that any given aircraft is missing component type i when there are k shortages of i across the fleet of NA(t) aircraft is k/NA(t). Therefore, the probability that any given aircraft has a shortage of item i is given by summing across the possible values of $k = \ell - s_i(t)$ times the probability they occur:

$$\sum_{\ell=s_i(t)+1}^{\infty} \frac{(\ell-s_i(t))}{NA(t)} \, p\,(\ell/\lambda_i(t) = \frac{EB_i(t)}{NA(t)} \qquad (22)$$

where $EB_i(t)$ is the expected backorders of component i. Assuming the failures are independent, the probability that an aircraft is NMC due to shortage of some item is

$$1 - \prod_{i=1}^{N} \left(1 - \frac{EB_i(t)}{NA(t)}\right) \qquad (23)$$

The expected number of aircraft NMC at time t is:

$$EN(t) = NA(t)\left[1 - \prod_{i-1}^{N}\left(1 - \frac{EB_i(t)}{NA(t)}\right)\right] \tag{24}$$

Equation 24 is applicable if each aircraft has only one of a given type of component. In the case of multiples of a given component, as in the example of a multi-engine aircraft, let Q_i be the quantity of item i on the aircraft and the following equations apply:

$$EN(t) = NA(t)\left[1 - \prod_{i-1}^{N} \sum_{y=o}^{NA(t)Q_i} \frac{\binom{Q_i NA(t)-Y}{Q_i}}{\binom{Q_i NA(t)-Y}{Q_i}} PB_i(Y)\right] \tag{25}$$

where $PB_i(y)$ is the probability that item i has y shortages at time t.

$$PB_i(y) = \begin{cases} \sum_{k=o}^{S_i(t)} P(k/\lambda_i(t)) & y=o \\ P(k+S(t)/\lambda_i(t)) & y>o \end{cases} \tag{26}$$

2. Average number of aircraft NMC with an instantaneous cannibalization policy, $EN_c(t)$.

$$EN_c(t) = \sum_{j=o}^{NA(t)-1} [1 - P(j)] \tag{27}$$

where P(j) is the probability that the number of aircraft NMC is less than or equal to j.

3. Total expected backorders. This is the sum of the individual component backorders from Equation 20, (here denoted by $EB_i(t)$):

$$EB(t) = \sum_{i=1}^{N} EB_i(t) \tag{28}$$

4. Probability of meeting aircraft missions. B(t) is the maximum number of allowable NMC aircraft that will still permit accomplishment of a stated level of missions; D(t) is that number of missions at time t; r(t) is the maximum number of sorties per unit of time by a single mission-capable aircraft,

$$B(t) = NA(t) - [D(t)/r(t)] \tag{29}$$

The probability of meeting mission demands is then PD(t) = P(j), where P(j) is the probability that the number of aircraft NMC is less than or equal to j.

5. The expected number of mission demands met, given k NMC aircraft, ES(t), is:

$$ES(t) = D(t)P(B(t)) + \sum_{k=B(t)+1}^{NA(t)} r(t)(NA(t) - k)PN_k(t) \tag{30}$$

Where $P(B(t)) = P(j) \equiv$ the probability that the number of NMC aircraft is less than or equal to j; j = B(t); and $PN_k(t) \equiv$ the NMC distribution function.

6. The probability distribution of the number of mission demands met. This is given by:

$$PSk(t) = \begin{cases} P(B(t)) & \text{if } k = D(t) \\ PN_j(t) & \text{if } k = r(t)(NA(t) - j); \\ & \quad j = B(t) + 1, \ldots, NA(t) \\ 0 \text{ otherwise} & \end{cases} \tag{31}$$

The variance in mission demands can then be figured from

$$VS(t) = D^2(t)P(B(t)) + \sum_{k=B(t)+1}^{NA(t)} (r(t)(NA(t) - k))^2 - ES^2(t) \tag{32}$$

Modeling the Pipelines. Dyna-METRIC forecasts the expected number of each aircraft component in each pipeline segment at any user-specified time of analysis. To do this, it computes component arrivals and a component delay function for each segment of the pipeline for each day in the scenario through the time of analysis. The base-by-base flying demands and component demand data drive the rate at which components arrive at each pipeline segment. If a component must pass through one pipeline segment before entering another, time delays in one segment may cause arrivals in another segment to be delayed. Those delays are represented as the probability that an arrival on each day of a scenario would remain in the segment at some later time of analysis.

The component arrivals and delays are computed for each day prior to the time of analysis, then multiplied together and summed over time to forecast the total expected components still remaining in the pipeline segment at the end of any given day (16:15-16).

The pipeline delays can be modeled in two ways. When modeling a two-echelon system (base-depot), there is simply an order and ship time (OST) delay when a part is requisitioned from the depot. When modeling a three echelon system (base-CIRF-depot), there is a repair and supply process with transportation delays to and from the CIRF.

In the base-depot system,a failed component is subject to a base repair delay to allow for diagnosis and attempted repair. This delay, by user decision, is either deterministic or random (exponentially distributed). The model then uses the base repair delay, combined with the OST delay to compute the expected number of each component on requisition (16:16-19).

In the base-CIRF-depot system, the model delays arrival of reparable components at the CIRF by the base repair time and the reparable component transportation time. The delayed arrival rates are used with the CIRF's repair delays to estimate the number of components in the CIRF repair pipeline segment (16:19).

The model assumes that the base will immediately order a replacement from the CIRF when a failed component is

determined to be NRTS. The base receives the item, if one was available, after a serviceable item transportation delay. If a serviceable component was not available in the CIRF stock, the order would be filled after one completed CIRF repair (16:20).

The model allows a CIRF to order replacements from the depot, subject to an OST delay. The model assumes a diagnosis and repair attempt delay at the CIRF and transportation delays to and from the depot.

In both the two and three echelon cases, the model totals the number of components in both on-base and off-base pipelines to estimate the total expected number of components in repair or on order at the base.

In steady state models, the average rate of flow through the pipeline from a unit is equal to the average rate of flow to the unit, that is, the retrograde flow equals the forward flow. The average flow for unit k can be given as $\bar{d}_k$. Transportation times can be termed as transportation delays. Assume there is a transportation delay, T_k^R, for the retrograde movement and a transportation delay, T_k^F, for the forward movement. The average repair time at the higher echelon is given by Υ. The average number of components in repair or in transportation is then λ_k^R, given by:

$$\lambda_k^R = \bar{d}_k(T_k^R + \Upsilon) \tag{33}$$

and the average number of components in shipment to the unit is λ_k^F, given by:

$$\lambda_k^F = \bar{d}_k \ T_k^F \tag{34}$$

If the higher echelon is supporting only one unit, the average total pipeline for a given component is the base repair pipeline for that component, $_k^B$, plus the averages shown in Equations 33 and 34:

$$\begin{aligned} \lambda_k &= \lambda_k^B + \lambda_k^R + \lambda_k^F \\ &= \lambda_k^B + \bar{d}_k(T_k^R + \Upsilon + T_k^F) \end{aligned} \tag{35}$$

[16:49-50]

The dynamic model requires introduction of the following variables, repeated here from Hillestad:

$\lambda_k^R(t)$	Average number of components from base k in transportation to or in repair at the next higher echelon at time t.
$\lambda_k^B(t)$	Average number of components in base repair at time t.
$\lambda_k^F(t)$	Average number of components in transportation to base k at time t.
$S^R(t)$	Supply level for the retrograde pipelines at time t.
$S_k(t)$	Supply level at base k at time t.

The average shortage in the retrograde transportation pipeline at time t is given by the expected backorders, $EB^R(S^R(t), \lambda_k^R(t))$.

This leads to the equation for the average pipeline at location k, which is:

$$\lambda_k(t) = \lambda_k^{\mu} + \lambda_k^{B}(t) \tag{36}$$

where $_k$ is the average unfilled orders at location k.

The addition of more locations served by the single higher echelon facility assumes that the supply level, $S^R(t)$, applies to all retrograde pipelines and that the shortages must be allocated back to the units. Therefore,

$$\lambda^R(t) = \sum_{k \text{ bases}} \lambda_k^R(t) \tag{37}$$

and the average shortages in the retrograde portion of the system are:

$$EB^R(S^R(t),\ \lambda^R(t)) \tag{38}$$

[12:56]

The shortages should be allocated to the various locations based on a criterion representing the way shortage allocations are made in real-world situations. One criterion is the time-averaged demand at the location. The allocation then becomes:

$$EB_k^R(t) = \frac{D_k^R(t,\Upsilon)}{\sum_{k \text{ locations}} D_k^R(t,\Upsilon)} \cdot EB^R(S^R(t)_1 \lambda^r(t)) \tag{39}$$

where $D_k^R(t, T)$ represents the average demands in the interval $(t-T, t)$ [12:57].

Pipeline Constraints. Limitations in repair resources affect pipeline quantities by creating backlogs when component failure rates temporarily exceed the capacity of repair facilities. Such situations may well arise during wartime when the the number of component failures increases due to increased flying demands.

Dyna-METRIC employs a mean-value simulation to determine the quantity of each component being tested or awaiting test at each base or CIRF. This simulation makes the assumption that the repair process for each component requires access to some critical repair resource. For simplicity, Dyna-METRIC represents all critical repair resources such as technicians, repair teams, and test equipment as test stands.

If the component failures exceed test stand capacity, arriving components may not be able to enter repair immediately. This results in a repair backlog. The parameters of this backlog (size and rate of increase) depend on the time-varying arrival rate of reparable components, the test stand time needed to repair the component, and the number of test stands available to repair the components. In Dyna-METRIC, each type of test stand can repair only certain (user-specified) components, and each type of component can be assigned to only one test stand type.

Dyna-METRIC allows for test stand downtime for maintenance, rest, or failure of test stand components. Dyna-METRIC adjusts the daily test time available for each type of test stand according to user-specified inputs and the number of colocated test stands.

To help meet one of the major objectives of wartime logistics, maximizing the number of available FMC aircraft, repair priorities can be adjusted so that effort is focused on those components that are grounding or degrading the capabilities of the most aircraft. Throughout the scenario Dyna-METRIC reassigns repair priorities for each test stand type so that those components most seriously affecting aircraft availability and capability are repaired first (16:20-22).

After the available daily test time is determined, the model adds the daily computed demands for each component to to its workload, allocates the available test time to components, and, based on that allocation, subtracts repaired components from the remaining workload. That remaining workload is used as the base or CIRF repair pipeline in subsequent computations (16:22-23).

Peacetime Pipelines. Dyna-METRIC computes pipeline quantities only for the flying hour-generated demands during the analysis period. Unless otherwise specified by the user, the model would begin the analysis period with zero pipeline levels. In the real world, the pipelines

would contain both failed and serviceable components generated by prior flying activities. Dyna-METRIC contains three techniques for creating these pre-scenario pipeline levels: static initialization, dynamic initialization, and dynamic bootstrapping.

The static initialization technique assumes a steady state flying program prior to the start of the scenario. Based on that program and its resultant repair and resupply times, the model initializes the peacetime pipelines that empty as the scenario progresses. To represent real world transportation cut-offs, these peacetime pipelines may be cut off as part of the scenario.

A similar capability exists to model dynamic peacetime flying programs (16:23).

The model has the capability to save pipeline levels at the end of one run and use them to initialize the pipelines at the beginning of the next run. This dynamic bootstrapping technique can be used when a single model run cannot accommodate the combined peacetime and wartime scenarios. This situation could result from a peacetime flying program that is extremely dynamic or extended (16:23).

Computing Requirements. Dyna-METRIC computes requirements for problem items, stock, or additional test equipment. To compute these requirements, the user must specify a wartime capability goal and a strategy for achieving that goal. For Dyna-METRIC, the wartime capability goal is the

minimum fraction of the aircraft fleet allowed to be NFMC with a given confidence level. The model accepts three strategies for attaining that goal: external operator intervention, buying spare parts, and buying additional test equipment. The first strategy involves redesigning the support system to eliminate or minimize support constraints. The model identifies a ranked list of components whose support must be improved to achieve the aircraft availability goals. The support can be improved by any combination of adjusted logistics factors, including reallocated stock levels, shortened repair times, increased reliabilities, or enhanced transportation and distribution (16:28-29).

The second strategy involves two sub-strategies: buying spares to ensure that each component will achieve the NFMC goal, or buying spares to ensure that all components jointly achieve the NMFC goal . With both of these sub-strategies the model suggests components and sub-components to buy to approach the NMFC goal at minimal stockage cost. If the user opts to have the model consider all all components jointly, the model first ensures that each component achieves the goal independently. The model then buys more components across the range of components to achieve the overall goal. It does this one step at a time at each base or CIRF, buying the component that provides the largest marginal increase to the location's probability of achieving the NMFC goal, at the least cost, until the goal

is met. Dyna-METRIC assumes that any user-entered initial stock levels represent an unrecoverable cost, so it retains that stock throughout the scenario and makes only marginal additions to stock to improve performance. Dyna-METRIC computes stock requirements for sub-components in much the same way, except that the model buys enough subcomponents to achieve the user-specified ready rate (16:30).

The third strategy addresses the test stand constraint. The model computes how much test stand time would be required if all failed components were repaired by the time of analysis. It then buys additional test stands to cover any shortfalls (16:31).

Dyna-METRIC Assumptions and Limitations. All models have limitations, that is, they are not perfect representations of the real world. Although many of the limitations of earlier models, including earlier versions of Dyna-METRIC, have been minimized, there remain factors that inhibit the model's ability to reflect reality. The limitations of Dyna-METRIC Version 4 are:

FMC Sortie Rates Independent of Flight Line Resources or Operational Plans. Dyna-METRIC assumes that the average FMC aircraft can complete a specified number of sorties each day. Flight line resources such as ground crews, fuel trucks, ground power units, etc. limit a base's ability to turn (recover, replace failed components, reload, and relaunch) aircraft. Operation plans may utilize

aircraft in such a way as to limit the efficient use of flight line resources, for example, by bunching sorties and causing backlogs in servicing the aircraft (17:31-35).

This limitation is the same as with earlier versions of the model, but Version 4 allows maximum turn rates to be established for each base (13:265).

Aircraft Interchangeability Assumption. The model assumes that all the aircraft at a base use the same components. It assumes the aircraft, and their sorties and components, are interchangeable. In the real world, however, this may not be the case. If some of the aircraft have a unique set of components added to the aircraft, the percentage of that base's aircraft with those components may be input to the model. The model adjusts for the unique components, and as long as there is only one aircraft type per base with a set of unique components, the NMFC rate will be accurate.

If a base has two different types of aircraft with totally different components, for example, F-15s and A-10s, the model will assume that components and sorties can be interchanged and compute an erroneous NMFC rate. This hazard can be worked around by splitting the base into hypothetical mini-bases, each with its own single type of aircraft. All base stock and repair capability is considered to be in a colocated CIRF that would serve the

minibases. Each of the mini-bases would have a 100 percent NRTS rate and no transportation lags (17:35-36).

Lateral Resupply Is Ignored. The model ignores the real world practice of shipping parts between bases to meet immediate demands that cannot be met by the normal resupply system. Version 4 allows for a work-around by having several bases being supported by a CIRF (provided the CIRF is not being used for any other purpose) to which has been relocated some of the bases' stock. Shipments from the CIRF to the bases simulates lateral resupply (13:16].

Economic Order Quantity and Consumables Ordering Policies Are Not Modeled. The mathematics of the model apply only to those items whose order quantity is one. With order quantities greater than one, such as those involving economic order quantities of low-priced items, the mathematics give only an approximately accurate result. Pipeline variability also increases with the order quantity.

To work around this limitation, the user can set the demand variance to mean ratio proportional to the square root of the order quantity. Expected variability in demand due to the order quantity will then be reflected in the pipeline variability (13:18).

Expected Backorders and Awaiting Parts Quantities Approximate Additive Pipelines. Isaacson, et al., describe this limitation as follows:

> The model does not compute the probabilistic effects of backorders and awaiting parts quantities with related pipelines. Rather, the expected values of these quantities are added to the appropriate pipelines as though they were also Poisson or negative binomial distributions [13:18].

When expected backorders or awaiting parts quantities are small, i.e., less than one, this limitation appears to have only a modest effect on computations of NFMC aircraft or base component breakdowns. As the expected backorders and awaiting parts quantities increase, the effect decreases (13:18).

Unconstrained Repair. Version 4 optionally constrains the repair capabilities at all echelons and permits separate peacetime and wartime depot daily production limits (13:266). When the constrained repair option is not used, the model assumes that demands arrive randomly with either a Poisson or negative binomial distribution, and transportation and repair times are from known distributions that are independent of demand.

If the constrained repair capability option is not employed, the model may underestimate or overestimate system performance (13:15].

The Constrained Repair Computations Are Approximations. The expected number of components in the pipelines for constrained priority repair are based on a deterministic, expected value computation that is an approximation of real world demand and repair processes. The

resulting pipeline distributions are applied as if they are independent, which they are not. Constraints on repair capacity cause components to wait while other components are repaired and the priority repair will seek to equalize the pipelines for all components. The repair computations will thus approximate real world system performance when the following conditions are met: (1) the demands for one component dominate all others, and (2) the combined demands for all components exceed the shop's capacity (13:17).

The specific modeling scenarios and input variables used in the comparison of EAC and Dyna-METRIC requirements computations are discussed in Chapter III.

III. Methodology

Overview

The overall objective of this research is to compare different methodologies for computing operational spares requirements for the F110-PW-100 jet engine and, based on that comparison, to recommend a specific model for use in computing modular engine requirements.

To answer the research questions, two investigative questions will have to be answered. This required that specific scenarios be developed that are realistic, yet compatible with each model.

To answer the first investigative question, "Will Dyna-METRIC and EAC computations result in the same requirements, given equal parameter?", the identical scenarios will be run through both the EAC and Dyna-METRIC models. Because Dyna-METRIC has features and parameters not contained in the EAC model, the user-specified parameters of the Dyna-METRIC model will be initially set as close as possible to those of EAC (that is, the Mod-METRIC segments of EAC). The scenarios were provided by AFLC/MMMRR, and were developed from several sources. Pipeline times were taken from Air Force Technical Manual TO 2-1-18, Aircraft Engine and Module Management by Operating Limits and Pipeline Times. Removal intervals were provided by

AFLC/MMMRR and were taken from the Actuarial Removal Interval Table (AFLC Form 283E) for the F100-PW-100 engine. The flying hour program is hypothetical, but it is considered by engine experts to be realistic for use in comparing the models.

To answer the second investigative question, "Can Dyna-METRIC parameters be adjusted to give the same level of support as EAC, but at less cost?", the results obtained from the requirements computations of both models will be assessed using Dyna-METRIC to determine which model achieved the highest level of support. The Dyna-METRIC parameters will then be varied to determine if the model can provide the same level of support as that provided by EAC, but at less cost . Previous research comparing Mod-METRIC and Dyna-METRIC indicated that Dyna-METRIC will ". . . recommend a smaller inventory of spares than the Mod-METRIC model while maintaining an equal level of performance" (18:vii). Although there will be no effort to duplicate the research done by Yauch, this research will attempt to generalize Yauch's result to engines and modules.

The EAC model will be run twice. The first run will be made using the engine only, that is, without modules, to test the scenario and model inputs. The second run will include modules. Several runs, at various confidence levels and parameter settings, are to be made with Dyna-METRIC. Following the same procedure used with EAC, Dyna-METRIC will

first be run without modules to test the scenario and other basic inputs. All subsequent runs will include modules (SRUs). Because research time is limited, scenarios involving subcomponents (sub-SRUs) were not developed.

General Scenario

The general situation to be modeled includes two USAF bases located in a relatively isolated overseas area. They are supported by a single depot located on the United States mainland. Base 1 is a large, multi-squadron, base colocated with a Queen Bee (CIRF). In peacetime, the base has a complement of 120 F-15s. At the onset of war, 48 of the aircraft deploy to Base 3 where they continue to be supported by the Queen Bee. Base 2 is a small, single squadron, base with a jet engine intermediate maintenance (JEIM) facility. At the onset of war, the 24 F-15s assigned to the base deploy to a Forward Operating Location (FOL). The Base 2 FOL will be completely cut off from resupply for the first 30 days of any war. Both the Base 2 FOL and Base 3 have limited organizational maintenance capability during wartime.

Scenario Used for EAC Computations

A target ready rate of 80 percent will be used for each run. In the runs which include modules, an initial target budget will be established, then in subsequent runs to attain a ready rate as close as possible to the 80 percent

target. The model does not provide for a target budget for engine-only scenarios.

Peacetime. Because Mod-METRIC is a two-echelon model, only bases and a depot will be included in the scenarios. The scenarios includes two overseas bases supported by a single CONUS depot. The model does not require that the number of aircraft be specified since it deals only with monthly flying hours. Figure 1 shows the peacetime relationship between the depot and bases.

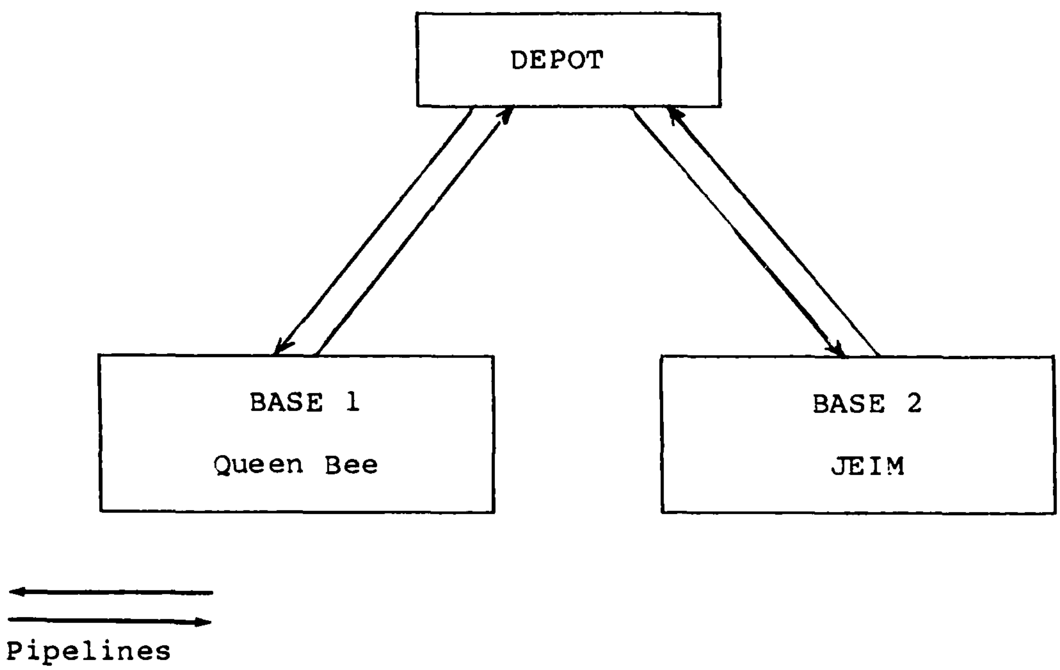

Figure 1. Peacetime Scenario

Base 1 is located 14 days order and shipping time (O&T) from the depot. Its aircraft fly an average total of 3100 hours per month.

Base 2 is also located 14 days O&ST from the depot. Its aircraft fly an average total of 650 hours per month.

The scenario fort Base 2 assumes that it is located 14 O&ST from the depot and has an in-place JEIM facility to which is sent all failed engines. Again, this is a peacetime assumption not explicitly modeled by Demand/ Resupply. The surge scenario assumes the 24 aircraft assigned to the base will deploy to a forward operating location, with the JEIM facility to follow in 30 days. The Base 2 FOL will be cut off from resupply, but will have a limited capability, called mini-repair, to remove, repair, and replace LRUs and SRUs. The incremental surge period flying program for the Base 2 FOL is:

Days	Flying Hours
1 through 5	550
6-10	350
11-15	250
16-20	250
21-25	200
26-30	200

The scenario assumes that Base 3 receives the 48 aircraft deplo''ed from Base 1. Base 3 is supported by the Base 1 CIRF, which is seven days transmit time away. The

base has mini-repair capability. The Base 3 incremental flying hour program for the surge period is:

Days	Flying Hours
1 through 5	1100
6-10	700
11-15	500
16-20	450
21-25	450
26-30	500

Figure 2 shows the surge period depot/base relationships.

Sustainment. The sustainment scenario assumes continuation of the pipeline between the depot and Base 1, and the re-establishment of support for Base 2. The Base 1 flying program is 2500 hours per month and the Base 2 program is 900 hours per month. Mod-METRIC is unable to model the CIRF-Base 3 relationship, so Base 3 is modeled off-line in accordance with EAC procedures. This procedure uses the daily demand rate, mini-repair rate, mini-repair time, and round trip transportation time between the base and CIRF to model this relationship. Base 3 is located 14 days round trip from the Queen Bee and has a sustained flying program of 1800 hours per month. Figure 3 shows the sustainment period depot/base relationships.

EAC Computations. All EAC computations will be done by AFLC/MMMRR and provided to the author as input for the experiment.

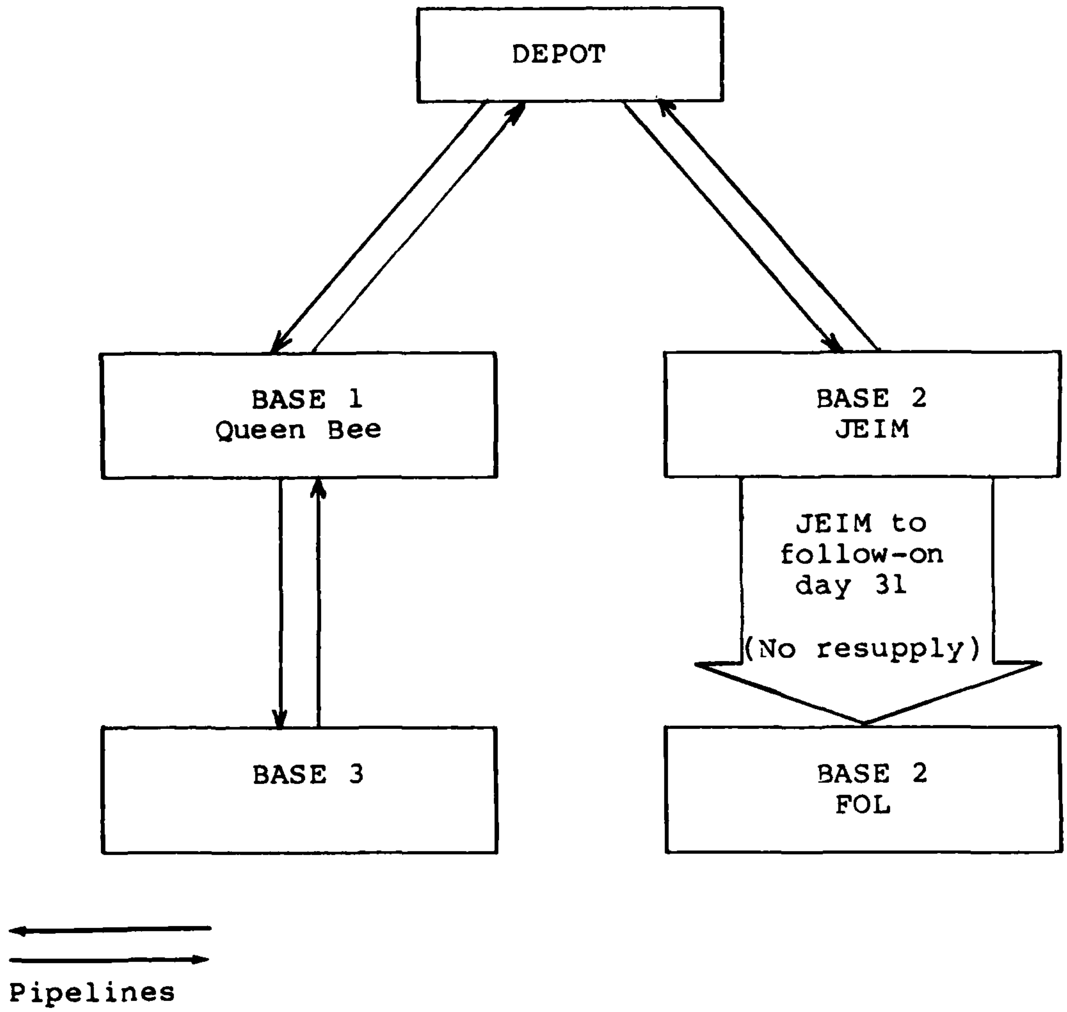

Figure 2. Surge Scenario

Dyna-METRIC Scenario

The general scenario for the Dyna-METRIC computations is the same as that used for EAC. Dyna-METRIC is able to model the dynamics of the transition from peacetime to war, so the distinction between the various phases of operations required by EAC is not as important when using Dyna-METRIC.

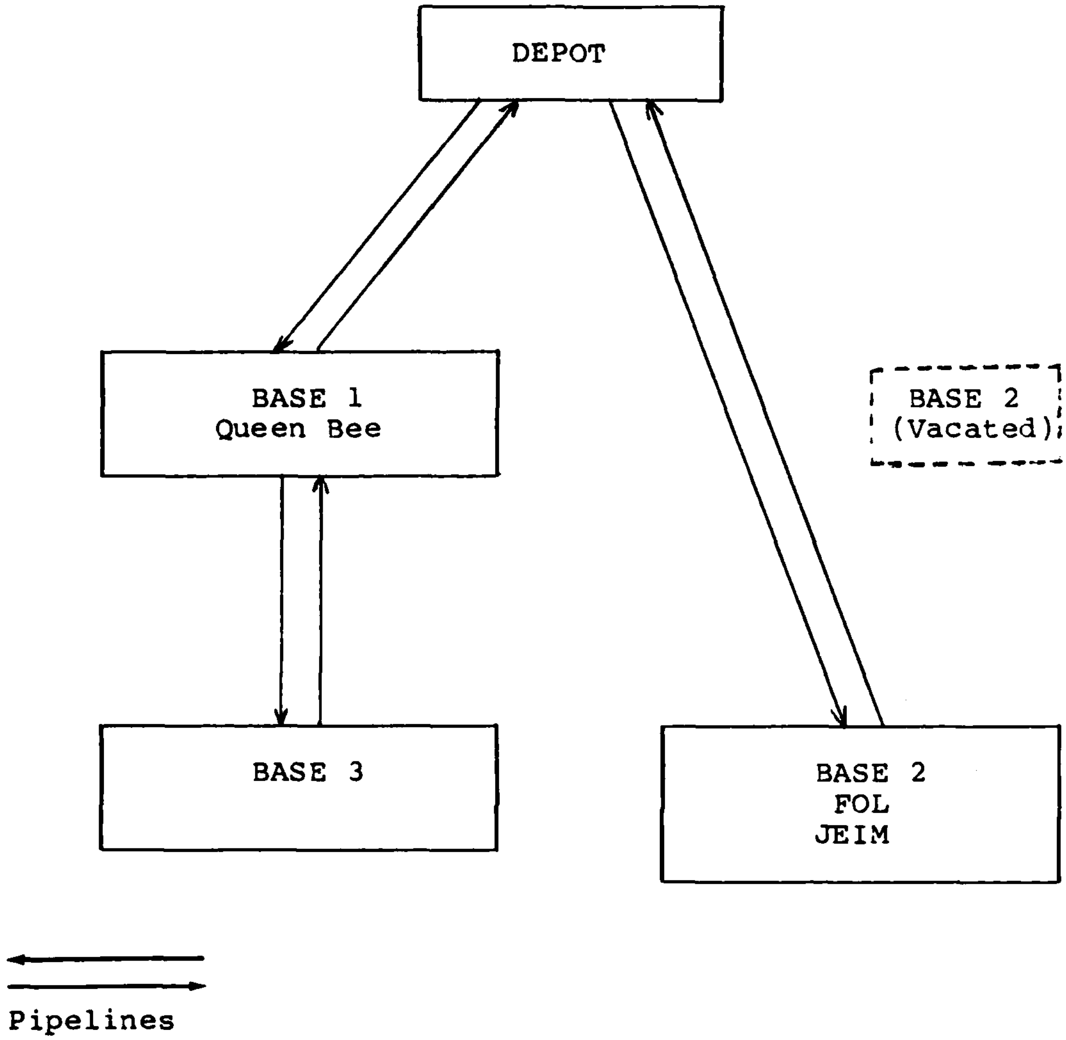

Figure 3. Sustainment Scenario

In general, peacetime conditions are represented as day 0 in Dyna-METRIC, the surge period is represented by days 1 through 30, and the sustainment period by day 31 and beyond. Because Dyna-METRIC contains more variables than EAC, the duplication of the scenario will not be exact. The author will minimize the amount of disparity caused by the

difference in model variables. To accomplish this it may be necessary to ignore certain features and variables as the Dyna-METRIC model permits, so that, at least in the initial comparison of the models, the full capabilities of Dyna-METRIC may be intentionally limited. This will provide the answer to Investigative Question #1.

After EAC has been used to compute the required stock levels based on the given scenarios, Dyna-METRIC will be used in the assessment mode to determine the level of performance generated by those stock levels. Then Dyna-METRIC will be used to compute requirements with a goal of attaining the previous performance levels. Dyna-METRIC parameters will then be adjusted in an attempt to maintain the same performance levels at a lower cost. This will answer Investigative Question #2.

Results of the experiment are discussed in Chapter IV.

IV. Results

Overview

Headquarters AFLC/MMMRR was unable to provide the EAC computation data needed as input for the experiment. The researcher attempted to accomplish the computation himself, but limited research time and the nature of the EAC model prevented completion of the computations and, therefore, the experiment as designed. During the course of attempting to compute requirements using EAC the researcher discovered what appear to be major problems inherent in the model that inhibit efforts to compare it to other models and limit it usefulness as a tool for computing engine requirement.

Discussion of Results

This research disclosed two major problems with the EAC model. Both involve computation of requirements for modules.

The first problem involve calculation of module requirements for the surge period. The Demand/Resupply model used to compute surge period requirements considers only engines. For bases with mini-repair capability, the requirement for a single type of module, augmentors, is computed manually. Requirements for other modules are not computed. The modules levels computed by Mod-METRIC for the sustainment period are used as the surge period levels (13). It appears

that the the surge requirement for modules would be greater than the sustainment requirement due to the higher level of flying hours. Published EAC procedures do not address this issue.

The researcher discussed this issue with an operations research analyst who works extensively with EAC at the San Antonio Air Logistics Center (SA-ALC/MMPYA). It was the analyst's opinion that all aircraft are assumed to deploy away from maintenance facilities during the surge period; therefore, only spare whole engines are needed to support surge operations. The researcher questioned the validity of this assumption with regard to situations wherein aircraft either do not deploy away from their maintenance facility, or deploy, but continue to be supported by a Queen Bee, as was the case for Bases 1 and 3 in the experimental scenario. The analyst stated that EAC does not, in fact, provide for this, ad that there is no guidance available as to how this situation is to be modeled.

The second problem involves module requirements for certain logistics support configurations during the sustainment period. Mod-METRIC is limited to two echelons of repair. The wartime scenario used in the experiment includes three repair echelons, as does the real world logistics support environment. The EAC work-around for this situation is to perform requirement for bases supported by a Queen Bee. This off-time computation involves only whole

engines, not modules. Even if it is assumed that all failed engines generated by operation as Base 3 are sent to the Base 1 Queen Bee for repair, modules are needed at the Queen Bee to effect those repairs. Adding Base 3 flying hours to those of Base 1 would allow Mod-METRIC to compute module levels, but they would be understated because Mod-METRIC is unable to model the pipeline between Base 1 and 3. There appears to be no way within EAC capabilities to accurately calculated the sustainment period module requirement for Base 3.

The lack of sustainment period module computation for Queen Bee-supported bases, as well as the assumption that surge period, may result in understatement of module requirements, and consequently to overstatement of the requirement for whole engines. The likely results is excess expenditures for the purchase of engines versus modules with no increase in operational capability. In fact, that capability may be reduced due to repair constraints caused by not having sufficient modules available.

The planned experiment included using Dyna-METRIC to assess the operational capability resulting from the EAC-derived stock levels. Dyne-METRIC would then be used in the requirements mode to compute requirements that would provide that same level of capability, thus allowing comparison of spares requirements as seen by each model. Since EAC is unable to accurately model the scenario as given, comparing

its computations to those of Dyna-METRIC, which can model the logistics relationships of the scenario, would require complete redesign of the experimental scenario. While the scenario could have been redesigned, doing so within the constraint of EAC would have resulted in an experiment of no useful value. These models are intended to capture the dynamics of realistic operating environments; that EAC cannot do so represents a significant flaw in the expected use of the model.

As discussed in Chapter I, experts in engine requirements computations believe EAC to be too time and labor intensive for general use. Also, the number and nature of manual calculation involved in computing requirements with EAC increase the likelihood of errors. The difficulties in using EAC were apparent to the researcher during the four week period in which he attempted to use the model to determine the requirements of the experimental scenario. Considerable expertise is needed to successfully use the model. This became even more apparent when several members of the AFLC/MMMRR staff transferred to other organizations within a short time period, leaving no one with the knowledge and experience require to use the EAC model.

V. Summary, Conclusions, and Recommendations

Summary of Research Effort

The goal of this research effort was to compare two different methodologies for computing operational spares requirements for the F100-PW-100 jet engine and, based on that comparison, to recommend a specific model for use in computing modular engine requirements. The two methodologies to be compared were the current requirements computation model, EAC, and Dyna-METRIC, which has a requirement mode that has not been used for computing modular engine spares. The comparison was to be accomplished by means of an experiment in which identical scenarios would be input to each model and the results assessed using Dyna-METRIC. During the course of attempting to perform the EAC requirements calculations, the researcher discovered major weaknesses in EAC's ability to model the given scenario. These weaknesses are:

1. The model does not compute surge period module requirements. This results from the steady-state nature of Mod-METRIC, which precludes its use for modeling the dynamic surge period flying program.

2. The off-line computation of sustainment requirements for Queen Bee-supported bases does not include modules. This second weakness results from Mod-METRIC's inability to model more than two echelons of repair.

Conclusions

Because of inherent flaws in the EAC model, operational comparisons of EAC and Dyna-METRIC will also be flawed, most likely resulting in understatement of module requirements and overstatement of whole-engine requirements.

Previous research indicates that Dyna-METRIC is at least equal to Mod-METRIC as a computational tool in initial provisioning of F-15 fuel system LRU's. Both models stocked equal amounts of lost cost/high failure rate items and avoided high cost/low failure rate items. Back order and aircraft availability performance was nearly equal. In other, more subjectively measured areas, Dyna-METRIC performed better than Mod-METRIC (not EAC) to Dyna-METRIC in a two echelon scenario (19:27). It is reasonable to assume that in a three echelon scenario, with the necessity to use work-arounds for Mod-METRIC's two echelon limitation, Dyna-METRIC's relative performance would have been even more adavantageous.

Because engines are considered to be both end items and components, and are managed differently than other aircraft components, there may be come reluctance to generalize Yauch's result to the case of engine requirements. However, the demonstrated weaknesses of the EAC model would seem to make such a conservative approach unwarranted.

Recommendations

The EAC assumption that sustainment period module stock levels are sufficient to support surge operations should be investigated. If the surge requirement for modules is, in fact, less than would be indicated by the high level of flying activity, then the sustainment stock levels may be sufficient, an additive must be developed to avoid overstocking complete engines. In either case, the user is still left with the problem of being unable, with current procedures, to compute module requirements for Queen Bee-supported bases. Although development of a work-around is possible, the introduction of a heuristic approach to the problems, or the addition of more off--line computations, would complicate a model that is already of questionable practical value.

Because of Dyna-METRIC's ability to model more complex environments, including dynamic operational situations and three-echelon logistics support systems, further efforts should be made to validate it for use in computing engine requirements. Because of the apparent flaws in the EAC model, its use should be discontinued and experiments to compare EAC and Dyna-METRIC should not be undertaken until those flaws are eliminated or minimized.

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Abstract

The purpose of this research was to compare different methodologies for computing operational spares requirements for the F100-PW-100 jet engine, and to recommend a specific inventory model to be used by the Air Force to compute requirements for all modular engines.

The models to be compared were the Engine Availability Concept, currently being used to compute F100 requirements, and Dyna-METRIC, which shows promise for use in requirements computations, but is now used only for capability assessment. The research found that the Engine Availability Concept has apparently serious flaws that precluded comparison of the models using the scenario developed for the experiment. The study recommends that use of, and reliance on, the Engine Availability Concept be suspended pending completion of further research.

The Engine Availability Concept model is time and labor intensive, and requires considerable user experience to operate. The model relies on an apparently unsupported assumption that engine module stock levels computed for one phase of a given wartime scenario can be used without modification in another phase. In addition, the model contains no provision for computing module requirements in situations involving more than two echelons of maintenance and supply.

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